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ENHANCEMENT OF THE NEUTRAL-BEAM STOPPING CROSS SECTION
IN FUSION PLASMAS DUE TO MULTISTEP COLLISION PROCESSES

By

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ENHANCEMENT OF THE NEUTRAL-BEAM STOPPING CROSS SECTION
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ABSTRACT

Multistep processes involving excited atomic states are found to produce a substantial increase in the stopping cross section for a neutral hydrogen beam injected into a plasma, and thus to reduce the beam penetration. For typical plasma and beam parameters of current large tokamak experiments, the stopping cross-sectional enhancement is found to vary from 25% to 50%, depending on the beam energy, plasma density, and impurity level. For neutral hydrogen beams with energies ≥ 500 keV, envisioned in tokamak and mirror reactor designs, the enhancement can be as large as 80-90%.

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High power, high energy neutral hydrogen beam injection has proved to be a very successful method for heating tokamak plasmas, and is a key element in producing, heating, and confining mirror plasmas.¹ Such beams are used on almost all current large fusion experiments. Calculations of the local time-dependent plasma heating rate from neutral injection, analysis of the ionized beam particle confinement, and neutral beam diagnostic measurements of the plasma profiles rely crucially on the accuracy of the beam stopping cross section.² This cross section is usually derived by considering only electron loss from the ground state beam atoms due to ionizing and charge-exchange collisions with plasma electrons and ions.

Recently, it was pointed out by Wieseemann³ that the neutral beam stopping cross section is increased by multistep processes, in which beam atoms are first excited by collisions with the plasma and are then ionized. Treating the problem by a two-state model, in which a single effective excited state was used to represent all the discrete excited levels, he found a 5-15% enhancement of the stopping cross section for beam energies below 100 keV and for densities in the neighborhood of 10^{14} cm^{-3} . The presence of excited states in a beam, arising in this case from the neutralization process, was appreciated early (~1960) in the mirror program, and the Lorentz ionization of these states was utilized for plasma buildup.⁴

In the present letter, we consider in detail the influence of multistep processes in the penetration of an energetic hydrogen beam into fusion plasmas. We explicitly include all hydrogenic levels up to the Lorentz limit and employ the presently best available cross sections for collisions with electrons, hydrogen ions, and impurities. We find an enhancement larger than that estimated by Wieseemann, and, in fact, sufficiently large to have an important effect on plasma studies related to beam injection and beam-plasma

diagnostics. As will be discussed later, this enhancement is important not only for tokamaks, but also for mirror plasma experiments.

In our calculations, the penetrating neutral beam is represented by N separate sub-beams, each corresponding to a given principal atomic quantum number n . The normalized intensities $I_n(x)$ of the sub-beams, at a distance x , satisfy the system of coupled equations

$$v_0 \frac{dI_n(x)}{dx} = \sum_{n'=1}^N Q_{nn'} I_{n'}(x), \quad (1)$$

where v_0 is the beam speed and Q is a matrix of reaction rates:

$$Q_{nn'} = -\delta_{nn'} [K_n^{(i)} + \sum_{n'' < n} (K_{nn''}^{(d)} + A_{nn''}) + \sum_{n'' > n} K_{nn''}^{(e)}] \\ + \theta_{nn'} [K_{n'n}^{(d)} + A_{n'n}] + \theta_{n'n} K_{n'n}^{(e)}, \quad (2)$$

with $K_n^{(i)}$ the rate for electron loss from state n due to ionization and charge exchange, $K_{nn'}^{(d)}$ the rate for deexcitation from n to n' due to collisions, $K_{nn'}^{(e)}$ the rate for excitation, and $A_{nn'}$ the radiative decay rate.⁵ (The symbol $\theta_{nn'}$ is unity if $n < n'$ and zero otherwise.) Processes inverse to ionization and charge exchange have not been considered, since, once ionized, the particle is considered to be lost from the beam. The system (1) is solved numerically subject to the condition that at $x=0$ only the ground state is populated. The normalized beam intensity at any point is, of course, the sum of the individual intensities.

The maximum principal quantum number N of populated states is given by the Lorentz ionization limit, $N = 1/2 (\epsilon_0 / |\vec{v} \times \vec{B}|)^{1/4}$, where ϵ_0 is the electric field of the nucleus evaluated at the first Bohr radius.

For typical conditions ($E \approx 50$ keV, $B \approx 3T$), one has $N \approx 7$. Excitations to levels higher than N are equivalent to ionizations; these are taken into account in the summation over $n' > n$ in Eq. (2). The upper limit of this sum was taken sufficiently high ($n \approx 80$) to ensure numerical convergence.

The cross sections for excitation from $n=1$ to $n=2$ and ground state ionization, due to both electron impact and proton impact, have been taken from Born-type extrapolations of experimental data.⁶ For the electron impact excitation/deexcitation and ionization processes involving excited states we have used the semi-empirical formulae of Vriens and Smeets.⁷ The proton and impurity ion impact excitation and deexcitation processes (except for $n=1$ and 2 in the proton case) have been calculated using a two-state close-coupling method with a dipole ion-atom interaction.⁸ The cross section for the proton charge exchange reaction with the ground state hydrogen atom has been taken from the experiment,⁶ while for the sum of the cross sections for the proton and impurity ion impact ionization and charge exchange with excited ($n > 2$) atoms (the electron loss cross section), we have used a recently derived scaling relation.⁹ The reaction rates $\langle \sigma v \rangle$ for the above processes have been computed from the cross sections using standard numerical integration techniques. The oscillator strengths for spontaneous radiative decay rates were taken from a standard approximation.¹⁰

We have characterized the results of our calculations by the fractional beam stopping increment

$$\delta = \frac{\lambda_0 - \lambda}{\lambda}, \quad (3)$$

where λ is the mean-free path including excitation effects and λ_0 is the mean-free path of the beam calculated with the ground state atoms only. δ is the

fractional increase in the beam stopping cross defined as $1/\lambda = n_e \sigma$. As Fig. 1 illustrates, δ is a strongly varying function of the beam energy and plasma density. The enhancement of the beam stopping is small (~ 10 -20%) at low beam energies ($E \lesssim 30$ keV), but becomes quite significant in the 50 keV range and above. In the low energy range (1-30 keV), electron impact collisions dominate the excitation and ionization rates, and charge exchange is the dominant electron loss mechanism. At energies above ~ 40 keV, proton collisions become dominant for excitation and ionization, and the ion impact ionization rate exceeds the charge exchange rate. As expected, the effect of multistep collision processes on the beam penetration also increases with plasma density. The effect of impurities is to increase δ (Fig. 1). δ turns out to be proportional to Z_{eff} (Fig. 2). Impurities have the largest effect on δ for the higher energy beams. Some of the increase in δ (dashed curves) is due to collisions of ground state atoms with impurities,¹¹ but the major increase is due to excitation effects.

The dependence of δ on the magnetic field strength was also examined and found to be very small for $2 \text{ T} < B < 15 \text{ T}$, as would be expected from the weak dependence of Lorentz ionization limit N on the magnetic field.

The results of present investigation have important implications for the neutral beam heated plasma experiments. The analysis and predictions of the performance of plasmas heated by neutral beams (local heating rate, beam particle confinement, etc.) are highly sensitive to the beam attenuation which, in turn, depends exponentially on the beam stopping cross section.

For example, the usual criterion that neutral beam heating provide adequate penetration is that $a/\lambda \sim 2$ to 4 where a is the plasma minor radius and λ is the mean-free path.¹² With such a requirement, the central heating rate would scale approximately as $(1 + \delta) \exp(-\delta a/\lambda_0)$. For a beam system

designed for a given a/λ_0 , a value of $\delta = 0.5$ would decrease the central heating by 45% to 80%. This would imply that tokamaks with high energy beam systems would have to operate at a much reduced density to achieve the designed central heating rate. Analyses of the radial profile of the energy confinement would also be in substantial error since the local heating rate would be calculated with a systematic error.

Interpretations of experimental data on different particle density profiles obtained by active beam diagnostic methods also depend critically on an accurate knowledge of the beam stopping cross section. Considerable effort has been devoted in the past to determine the effects of impurities on beam penetration.¹¹ As Fig. 2 shows, the influence of multistep processes on beam penetration (and plasma properties related to it) is even more important than the effects of impurities in the absence of excitations. The 80-100% increase of the beam stopping at energies above 500 keV implies that the beam energy has to be increased by the same percentage in order to achieve a given penetration depth. The results thus have serious consequences for the design and operation of negative ion based neutral beam systems. At beam energies above 40 keV/amu, both the ground state and excited state stopping cross section scale as $1/E$. Since $\lambda \sim E/n_e$, compensation of a decrease in λ due to excitation effects requires either raising the beam energy E or decreasing the plasma density n_e .

On the other hand, the enhancement of the beam stopping power due to multistep processes has beneficial effects on the large mirror plasma experiments. In many current designs of such experiments, the beam energy is limited by the requirement that at least 20% or so of this energy (typically 300-500 keV) be stopped in the mirror plasma.¹³ If the stopping cross section is increased by 60-100%, then either the beam energy can be increased or the

beam power can be reduced (by the above percentage) to obtain the same level of performance.

In summary, our calculations have shown that the enhancement of the stopping cross section of energetic neutral hydrogen beams injected into fusion plasmas may be as large as 25-50% for experiments such as TFTR and JET, which have beam energies of 60-80 keV/amu, and as large as 80-90% for the very high energy (300-500 keV) beams proposed for the large tokamak and mirror experiments.

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FIGURE CAPTIONS

- FIG. 1. Enhancement of the beam stopping cross section due to excitations, calculated for four electron densities as a function of beam energy. The electron temperature is taken as $E/10$ for $E < 100$ keV and as 10 keV for $E > 100$ keV. The solid curves are for $Z_{\text{eff}} = 1$, and the dashed curves are for $Z_{\text{eff}} = 3$ produced by carbon, oxygen, and iron in the ion density ratio 10:10:1.
- FIG. 2. The beam stopping cross section enhancement as a function of Z_{eff} for carbon, oxygen, and iron impurities in the ion density ratio 10:10:1, at four beam energies. The solid lines include the effects of excitations, while the dashed lines include only the effects of electron loss from the ground state.

FIG. 1

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FIG. 2

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